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Oblique Langmuir solitons and their self-compression in the "free-flight" regime

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For the first time we have observed experimentally in a magnetized collisionless plasma, of the "beam afterglow", slow (approximately fixed relative to the plasma) oblique Langmuir solitons with an HF carrier on the branch of waves with the linear dispersion $\omega = \omega_p \cos\Theta$, which occur as a consequence of the modulational instability of the nonlinear waves. The longitudinal size of the solitons is less than the initial (beam) wavelength and it is impossible to call them envelope solitons. We show that after a time equal to their "free-flight" (along with the plasma) along the magnetic field—after the "pump beam" was switched off—the solitons experience appreciable self-compression. The solitons observed differ in priniciple from the well known, fast, soliton [H. Ikezi, P. J. Barrett, R. B. White, and A. Y. Wong, Phys. Fluids **14**, 1997 (1971); S. M. Krivoruchko, Ya. B. Faĭnberg, V. D. Shapiro, and V. I. Shevchenko, Sov. Phys. JETP **40**, 1039 (1975); V. D. Fedorchenko, Yu. P. Mazalov, A. S. Bakaĭ, A. V. Pashchenko, and B. N. Rutkevich, JETP Lett. **18**, 281 (1973)], which exists on the same branch of waves: the fast soliton moves several orders of magnitude faster, constitutes a potential hump without an HF carrier and arises as the result of another mechanism, such as a Korteweg–de Vries ion-sound or shallow-water soliton [H. Ikezi, R. P. H. Chang, and R. A. Stern, Phys. Rev. Lett. **36**, 1047 (1976); B. B. Kadomtsev, Collective Phenomena in a Plasma, Nauka, Moscow, 1976, Ch. 3, §3; Ch. 5, §5 (English translation published by Pergamon Press)]. The observed solitons with oscillation frequencies $\omega = (1/3 \text{ to } 1/2)\omega_p$ are as yet not described in the theory.

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1. STATEMENT OF THE PROBLEM

The present paper is an extension of Refs. 1 and 2, in which we observed and studied Langmuir solitons in a magnetized collisionless plasma which was excited by an electron beam. In contrast to the preceding work[1] the aim of the present paper consisted in studying the evolution of the solitons *after* the "pump beam" was switched off, i.e., in the afterglow of the beam plasma. Such a study (if we neglect isolated observations in our first paper[2]) has not been made before. To carry it out it is necessary that the plasma be collisonless, i.e., that there be sufficiently low densities of both charged and neutral particles. It was just the high den-

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sity of neutral particles (an argon pressure $p \gtrsim 1$ to 2×10^{-4} mm Hg) which made it impossible for American investigators[3,4] to observe Langmuir solitons after the pump beam was switched off: due to electron-atom collisions the Langmuir oscillations were damped after a fraction of a microsecond, i.e., on the scale of the characteristic times of the problem they turned in reality to be unobservable.

In order to minimize the neutral-gas (hydrogen) pressure we again used, after the experiments performed in our previous work,[1] a linear delay of the gas with narrower diaphragms—the same as in our original experiments.[2] For this reason also the diameter of the plasma filament $2a$ was in the present experiments approximately one half that of Ref. 1, namely $2a \approx 3$ cm.

This change in the geometry of the experiment turned out to be completely sufficient to produce a collisionless plasma regime. Moreover, this change was very important to affect the possibilities for observing various waves. Indeed, we shall see below that the decreased plasma filament diameter turned out to be smaller than the wavelength of the electron oscillations excited in the plasma by the beam. It is well known that in such a situation the frequency of the excited waves is less than the Langmuir frequency and the waves are called "oblique Langmuir" waves, rather than Langmuir waves. The linear dispersion of such waves is given by the Trivelpiece-Gould formula[5]

$$f=f_p\cos\theta=f_p\frac{k_\parallel}{(k_\parallel^2+k_\perp^2)^{1/2}}, \tag{1}$$

where $k_\parallel=2\pi/\lambda$ and $k_\perp \approx 1/a$ are the longitudinal and transverse wave numbers, λ is the wavelength of the oscillations, $f_p=\omega_p/2\pi$ is the electron Langmuir frequency, while $f_p<f_H$, where f_H is the electron Larmor frequency.

The other experimental conditions and its methodology remained as before.[1,2] The plasma density $n=3$ to 4×10^9 cm^{-3}, the longitudinal magnetic field $H=2\times10^3$ Oe, the electron temperature $T_e\approx10$ to 20 eV, the pressure of the residual gas (hydrogen) $p_0\lesssim5\times10^{-6}$ mm Hg, the length of the plasma filament ~200 cm, and the speed of the plasma motion $v=2$ to 6×10^6 cm/s. Typical beam parameters are: electron energy $W_1=2$ to 2.5 keV, current density $I=2$ to 2.5 A, beam density $n_1\approx(0.1$ to $0.2)n$, and beam pulse length around 20 s. Under those conditions the plasma frequency $f_p=500$ to 600 MHz, the speed of the electron beam $u_0=2.5$ to 3×10^9 cm/s, the wavelength of the Cherenkov Langmuir wave, excited in the plasma by the beam, $\lambda_p=u_0/f_p\approx5$ cm $>2a$, and the waves are oblique Langmuir waves.

The plasma speed was measured through the time-shift of the ion saturation currents on mesh probes placed in different positions in the plasma filament. The propagation speed of the waves was measured by means of the same probes which were connected to two independent selective tunable P5-19 wave receivers, tuned to the same frequency. This method of measurement enabled us to observe the evolution of the waves in a single shot of the beam. To measure the plasma density wells and bunches (and also the time-dependence of the density itself) we applied as before[1,2] a quarter-wave resonator; we used it also to make independent measurements of the plasma speed.

In the analysis of the results obtained in this paper it is important to take into account the following fact. As in Ref. 1 we used as electric field indicators hf mesh probes with their plane oriented at right angles to the magnetic field. The probes therefore selected from all waves which exist in the plasma filament only those in which the electric field vector has a significant component parallel to the magnetic field. Correspondingly one could register from all hf waves propagating along the magnetic field either the purely longitudinal (Langmuir) waves, or the oblique Langmuir waves.

2. EXPERIMENTAL DATA

The basic results of the experiments consist of the following.

1. In the afterglow plasma, i.e., after the electron pump beam was switched off, we observed during a very long time (up to 100 to 200 μs) oblique Langmuir waves with frequencies $f=150$ to 350 MHz $<f_p$ corresponding to the branch (1) of Trivelpiece and Gould. The above-mentioned time of the existence of the waves must be considered to be rather long, as the period of the oscillations is only a few nanoseconds. Figures 1 to 3 illustrate the waves in the afterglow of the beam discharge; shown in those are both the time-dependence of the plasma density and the oscillagrams of the observed envelope of the hf wave amplitude.

2. It is already clear from Figs. 1 to 3 that the observed waves are grouped in bunches in which the characteristic time for the change in the envelope of the amplitudes of the oscillations is a few microseconds, i.e., of the order of thousands of oscillation periods. The wave bunches considered are thus solitary waves with an hf filling.

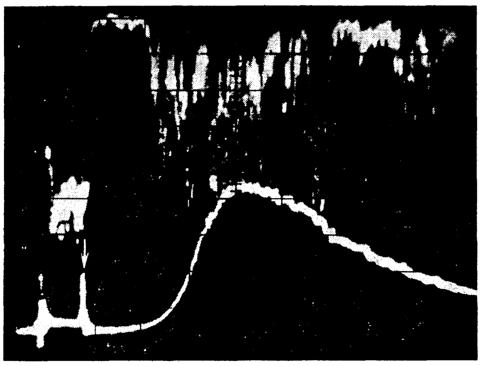

FIG. 1. Oscillograms of signals from the plasma density indicators (lower trace, deflection of the ray upwards) and of the envelope of the amplitudes of the hf electric field of the waves (upper trace, deflection of the ray downwards) time base 25 μs per division. The indicators are positioned at the end of the plasma filament at a distance $L\approx140$ cm from the discharge chamber plasma source. As in all other oscillograms of the present paper the density wells are indicated by a deflection of the ray in the lower oscillogram downwards; the arrow indicates the moment when the electric pump beam is switched off.

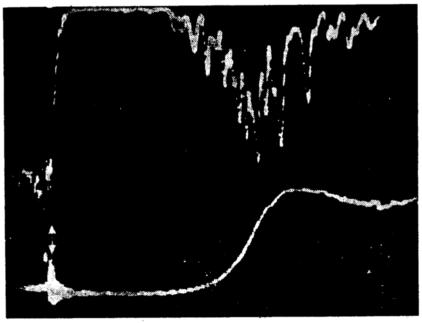

FIG. 2. Oscillograms, similar to Fig. 1, $L = 160$ cm. The speed of motion of the plasma $v \approx 2.5\times10^6$ cm/s. The observed frequency of the oscillations $f = 275$ MHz, the plasma density $n = 4\times10^9$ cm^{-3}, time base is 10 μs per division.

3. One can easily use the oscillograms given here to estimate the speed with which the wave bunches and the plasma move as the ratio of the separation distance (L) of the hf field and plasma density indicators from the discharge chamber source of the plasma to the free flight time, which is approximately equal to the time passed from the moment that the electron pump beam was switched off to the moment that the bunches and the plasma (of a given density) were registered. It is clear from the oscillograms that the wave bunches move together with the plasma with a velocity v equal to a few times 10^6 cm/s. By multiplying this velocity which was different under different conditions) by the length of the wave pulses and the intervals between them we determine (as in Refs. 1,2) the characteristic size of the wave bunches and the distances between them.

4. The observed waves are characterized by a sharp modulation of their amplitude (Figs. 1 to 6) with clearly separated spatial periods: $\lambda_M = 5$ to 6 cm $\approx \lambda_0/2$ and $\lambda_M = 10$ to 12 cm $\approx \lambda_0$, where $\lambda_0 = u_0/f$ is the initial wavelength of the wave excited by the beam in the plasma (when $u_0 = 2.5\times10^9$ cm/s and $f = 2.5\times10^8$ s^{-1}, $\lambda_0 = 10$ cm). The characteristic longitudinal size of the wave bunches is ~4 cm, i.e., of the order of the diameter of the plasma filament.

5. We observe in the afterglow of the beam plasma a modulation of its density which has the form of wells and bunches which are approximately correlated with the bunches of the electric field of the waves—Figs. 1 and 3. On the whole the picture of the field of the waves and of the modulation of the plasma density looks, as in the earlier experiments,[1,2] as in the development of Langmuir turbulence.[6,7] Therefore, starting from what we said under 2 and basing ourselves upon the experiments of earlier papers[1-4] we assume that the observed wave formation can be assumed to be oblique Langmuir solitons with hf carrier.

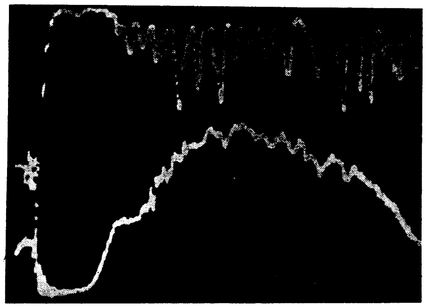

FIG. 3. Oscillograms, similar to Figs. 1,2, but $L = 110$ cm, $v \approx 2\times10^6$ cm/s. Time base 10 μs per division. The distance between the field bunches is 5 to 10 cm, the characteristic size of the bunches is ~4 cm.

6. The wave bunches propagate along the apparatus without spreading. This is clear, in particular, from Figs. 4 and 5 where we give the oscillograms of the signals from two probes which are positioned at different distances from the plasma source; the distance between the probes is 94 cm. The data of Figs. 4 and 5 were obtained in a single shot of the beam by means of two independent oscillation receivers tuned to the same frequency. It is clear that under the conditions of Figs. 4 and 5 the observed wave bunches traverse a distance of ~100 cm, moving along the magnetic field during ap-

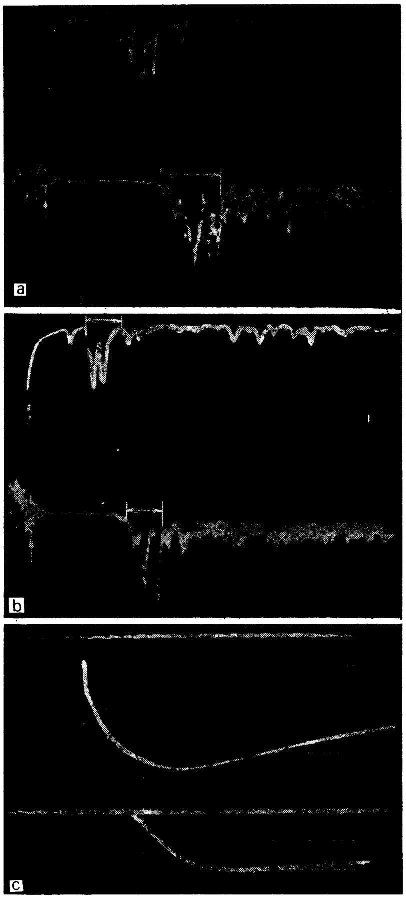

FIG. 4. a,b) Oscillograms of the signals from two identical indicators of the electric field of the waves, separated from one another by 94 cm (a) and 80 cm (b) and tuned to the same frequency $f = 250$ MHz; c) time-dependence of the plasma density in two sections of the plasma filament separated from one another by 94 cm. Time base 10 μs per division. The time shifts of the oscillograms of the signals from the field and density detectors, connected with a separation between the two probes of 94 cm are approximately the same. The horizontal arrows indicate the longitudinal dimensions of the wavepackets.

proximately 15 μs without spreading: the width of separate pulses which constitute the wavepacket, the distance between them, and the total width of the wavepacket do not change while the packet propagates along the apparatus. Hence, the observed wavepackets are essentially non-linear as a linear wavepacket spreads rapidly—already over a distance of the order of its width.[2]

We must make the following methodological remark in connection with the form of the oscillograms of Figs. 4a, b and Fig. 5. The impression may be created that the lower trace on those oscillograms has an appreciable dead time. However, this is not the case: the upper and lower oscillograms of Figs. 4a, b and Fig. 5 turn out to be totally synchronous, if they refer to the same signal (from the hf probe in a fixed position), supplied parallel to the inputs of the two receivers.

7. The wave bunches are localized in the plasma: they are approximately fixed with respect to the plasma and move relative to the apparatus together with the plasma. The speed of the wave bunches and the plasma is close to the ion-sound speed in atomic hydrogen: $C_s = 2$ to 5×10^6 cm/s (the upper limit corresponds to $T_e = 20$ eV). The conclusion about the localization of the observed non-linear waves in the plasma was reached from a comparison of their propagation speed relative to the apparatus with the speed of the plasma and is illustrated by Figs. 4 and 5. In those figures we compare the oscillograms of the time shifts of the signals from two hf probes, positioned at a distance of 94 cm from one another and the time shifts of the oscillograms of the signals from two plasma density indicators positioned with the same separation between one another. It is clear that the time needed to traverse a distance of 94 cm is ~15 μs both for the wave bunches and for the plasma itself; the speed of the waves with the plasma (on average) is $v \approx 6\times10^6$ cm/s.

The results similar to those formulated under 6 and 7 and obtained for a smaller speed of plasma flow ($v \approx 2\times10^6$ cm/s) are shown on Fig. 6. The oscillograms of Fig. 6 were taken with the help of one and the same wave-field indicator shifted from its original position to various distances along the plasma flow. In contrast to Figs. 4 and 5 they were obtained in different shots of the beam. Under the conditions of Fig. 6 the wave bunches also propagate without changing their form and it turns out that the time they move along the apparatus is approximately the same as the time the plasma moves along it: as under the conditions of Figs. 4 and 5 the wave bunches are frozen into the plasma.

The observed wave bunches are thus either fixed with respect to the plasma or move relative to it with a speed which does not exceed the ion-sound speed C_s. But that speed is, under the conditions of our experiments, three orders of magnitude smaller than the characteristic speed of the propagation of the linear waves with the dispersion law (1). This fact once again indicates the essential non-linearity of the oblique Langmuir waves studied here.

8. The observed non-spreading wave bunches reveal a time-dependence which is clearly noticeable in Figs. 4 and 5. For example, whereas on the upper oscillogram of Fig. 5 in a number of places one can see only incipient electric field peaks, on the lower oscillogram of that figure at the same spots (shifted along the magnetic field over 94 cm) distinct field bunches with a noticeably increasing amplitude start to form after 18 to 20 μs. As we indicated already the total length of the set of wave bunches (indicated by horizontal arrows) is the same on the two oscillograms of Fig. 5 (as, by the way, also in Figs. 4 and 6). Thus, Fig. 5 is one example of self-compression (modulational instability) of waves; under the conditions of this figure the growth rate of the instability is

$$\gamma \gtrsim 10^5\ \mathrm{s}^{-1} \approx \frac{m}{M} f_p, \tag{2}$$

where m and M are the electron and proton masses. Another example of the self-compression of waves is demonstrated in Fig. 4b where the wavepacket consists altogether of two field bunches. It is clear that after

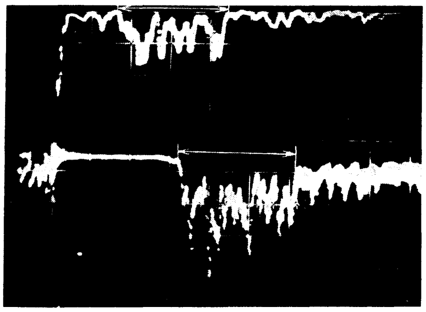

FIG. 5. Oscillograms of the signals from two wave field indicators separated from one another by 94 cm. Time base 10 μs per division. During the flight time the total length of the wavepacket (indicated by horizontal arrows) is not increased and its separate components become sharper and narrower (self-compression).

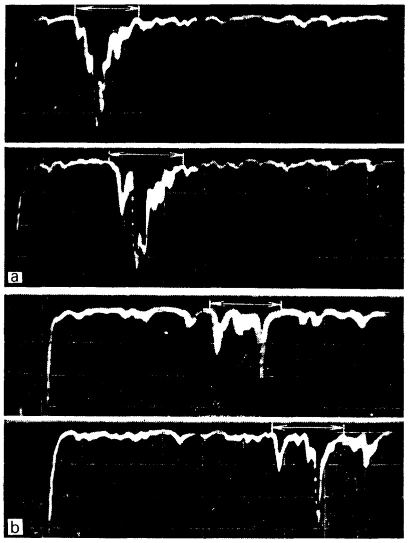

FIG. 6. Oscillograms of the signals from the same wave field indicator shifted from its original position over different distances "along the flow" of the plasma: a) 30 cm, b) 20 cm. Time base, respectively, 25 and 10 μs per division.

moving a distance of the order of 100 cm the wave bunches are somewhat compressed which is described by the oscillograph trace no longer with a continuous line but rather with separate points.

Further examples of the self-compression of the waves studied here are contained in the more detailed variant of the exposition of the work given here (see Ref. 8).

9. The lifetime of the observed packets of oblique Langmuir waves (solitons) in their "free flight" regime (i.e., when there is no pump) is clearly longer than 20 to 30 μs, i.e., a quantity of 10^4 periods of the oscillations. During that time the solitons certainly succeed in passing through the major part of the length of the apparatus without spreading.

10. As regards the mechanism for the self-compression of the non-linear oblique Langmuir waves, as a result of which the observed solitons are formed, the experimental data allow us to express the following assumptions. Since, as we showed above, the characteristic length for the wave modulation λ_M is less than or of the order of the original wavelength (i.e., in the modulation process the hf carrier is abruptly "interrupted") the self-compression mechanism of the waves is, apparently, of the same nature as in the experiments of Refs. 1 and 3, where it is caused by a variant of the modulational instability–the so-called OTSI.[1)] This mechanism is, apparently, not connected with the well known Lighthill criterion[9,2] which refers to the occurrence of an envelope soliton ($\lambda_M \gg \lambda_0$), i.e., to such a situation when the hf carrier of the wavepacket changes adiabatically.

11. The frequency spectrum of the oscillations (synchronous with the lower frequency[1]) of the observed solitons has a band of ~40 MHz, although the full width of the spectrum exceeds 200 MHz. We observe among the occurrence of bunches of oscillations on different sections of the frequency spectrum a clear time shift: the oscillations with lower frequencies appear on the distant hf probe appreciably later. For instance, on the probe at a distance of ~100 cm from the plasma source, waves with a frequency of 150 MHz occur about 10 to 12 μs later than the waves with a frequency of 200 MHz and about 20 μs later than the waves with a frequency of 250 MHz, and so on. This fact suggests a cascade build-up of the waves in the plasma–as a result of collective processes in their scattering and decay.[9]

In the present paper we have thus observed for the first time slow (approximately fixed relative to the plasma) oblique Langmuir solitons which appear as a consequence of the modulational instability of the waves of the Trivelpiece-Gould branch. The energy characteristics of these solitons, their transverse structure, frequency spectrum, and their formation mechanism need yet a more detailed study.

To avoid confusion we note that the slow oblique Langmuir solitons with hf carrier observed in the present paper must not be confused with the completely different—fast—solitons of the volume charge which exist on the same branch (1) of the Trivelpiece-Gould waves and which have been observed in a number of experiments.[10-12] A fast soliton[10-12] is a solitary potential hump without hf filling and its extension is of the order of the diameter of the plasma filament. It moves with a velocity of the order of the velocity of the linear Trivelpiece-Gould waves, approximately equal to the speed of the beam electrons, i.e., at least three orders of magnitude faster than the solitons observed in the present paper. Finally, this soliton arises not as a result of the evolution of the modulational instability, but as a consequence of Korteweg-de Vries mechanism—similar to the solitons on shallow water[9] or ion-sound solitons.[9,4]

[1)]The nomenclature OTSI (oscillating two stream instability) is the name of the aperiodic (stronger) variant of the modulational instability. Another equivalent nomenclature is modified decay (concerning the nomenclature see, for instance, Ref. 2).

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